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Rheology Study of Plant Oil for Marine Application

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Abstract

Environmental issues are among the main concern nowadays. Interest in developing environmental products arises concurrently with the industrial development. The use of plant oil as hydraulic fluid would help to minimize hazardous pollution caused by accidental spillage, lower disposal costs of the used fluid and meet the environmental regulations. This research was conducted to investigate the rheology elements and potential of plant oil in marine application. The properties and characteristics of plant oil were done via rheological study by focusing on the viscosity effect as a function of temperature and shear rate. The rheological models indicate that this plant oil belong to pseudo-plastic category. Further analysis was done to fit the experimental data with various models and the findings show that the Cross and Carreau models fit well with the experimental data. The plant oil was used in 1000 hour operation in a hydraulic system, built in the Universiti Malaysia Terengganu. The overall results suggest the potential substitution of plant oil as an energy transport media in marine application.

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1. Introduction

Development of natural based product is one of the alternatives to protect the environment from hazardous materials. Plant oil such as jojoba oil, coconut oil and palm oil has been studied thoroughly because of its environmental friendly characteristic [1]. Furthermore, the wide range of application exhibits by these oils had also increase interest in this field. Numerous researchers have conducted studies on plant oil and found that these plant oils are suitable to be used as biodiesel, alkyd resins, printing inks, lubricants and cosmetics products [2].

The construction of mega structure including ship, desalination plant and offshore structure symbolized the rapid growth of marine industry. Hence, the demand on lubricant, fuel and hydraulic fluid is also increase [3]. The existing lubricants, fuel and hydraulic fluid in the market is mineral based or petroleum based oil in which can bring harm to the environment and ecosystem in the case of leakage or spillage [4]. Legislative and moral concern has caused International Maritime Organization (IMO) to endorse the Annex VI of the MARPOL 73/78 convention which associated in controlling the ship emissions.

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Plant oils are suitable to be used in marine application because of its high biodegradability (95% of plant oils is biodegradable). Other attributes are high natural viscosity (30-80% higher than mineral oils), excellent lubricity due to ester functionality and high flash point [5]. Lubricity study of various plant based oils has been made by various researchers [6-10]. Palm oil methyl ester specifically was investigated by using four ball tribometer [11].

Viscosity is a direct indication on the stickiness of the fluids under studied. Higher viscosity indicates higher stickiness of the fluids and vice versa. Viscosity is the derivation of the relationship between shear stress and shear rate which can be expressed as shown in Eq. (1) [12]:

$$\eta = \tau / \frac{du}{dx} \tag{1}$$

where: τ is the shear stress (Pa); *du/dx* is the shear rate (1/s); and η is the viscosity (or dynamic viscosity) (Pa.s). An increasing of shear stress leads to a greater portion increase in shear rate and hence reducing viscosity value as indicated by viscometer. This phenomena is known as shear thinning behavior while for inverse observation, it exhibits shear-thickening.

Shear thinning behavior can be modeled by various models. They are Power Law, Cross, Carreau, Hershcel-Bulkley, etc. These equations are presented in sequence as shown in Eq. (2) – Eq. (5) [13]:

$$\eta = K_p \gamma^{n_p - 1} \tag{2}$$

$$\eta = \eta_{\infty,\gamma} + \frac{\eta_{o,\gamma} + \eta_{\infty,\gamma}}{1 + (\alpha_c \gamma)^m} \tag{3}$$

$$\eta = \eta_{\infty,\gamma} + \frac{\eta_{o,\gamma} - \eta_{\infty,\gamma}}{[1 + (\lambda_c \gamma)^2]^N} \tag{4}$$

$$\eta = \eta_o + \eta' \tag{5}$$

where: K_p is the consistency index (Pa.s^n); η_P is the flow behavior index (dimensionless); $\eta\infty_{,\gamma}$ is the viscosity at infinite-shear rate (Pa.s); $\eta_{o,\gamma}$ is the viscosity at zero-shear rate (Pa.s); λ_c and α_c are the characteristic relaxation time (s); η_o is the yield stress-viscosity at initial flow condition (Pa.s) and $\eta^{'}$ is the Bingham plastic viscosity (Pa.s). The effect of temperature was used where it usually fitted with Arrhenius type relationship which is shown subsequently in Eq. (6) [14];

$$\eta = \frac{AE_a}{RT} \tag{6}$$

where η is dynamic viscosity (Pa.s); A is pre-exponential factor (Pa.s); E_a is activation energy (J/mol); R is the gas constant (J/mol/K); and T is the absolute temperature (K).

This study was conducted to study the rheological aspects of plant oils as well as its performance specifically for marine application. This present work would help to promote the application of natural resources as well as to protect the environment. For the betterment of mankind, environmental friendly and sustainable source of bio-lubricant is to be sought for future use.

2. Materials and methods

Evaluation of plant oil for marine application was divided into rheology study and plant oil performance evaluation. Rheology study consists of lubricity measurements and modeling of the experimental data according to various models.

2.1. Rheology study

Viscosity measurement of plant oil was conducted by using Brookfield (Viscometer DV-I+) rotational type viscometer. Before use, the viscometer (accuracy ±1% full scale range; repeatability, 0.2% full scale range) was calibrated with 4.7 cP Brookfield silicone viscosity standard. The viscosity of the oils was measured in triplicate at ten different shear rates. SP-18 spindle was operated at different speeds between 3 and 100 rpm. A temperature controller (temperature accuracy of ±1%) was used to increase the temperature of the oil samples from 40 up to 100°C, the oil samples were left 15 minutes until steady state heat transfer was achieved.

The viscosity and percentage of torque were manually recorded when the viscosity reading reached apparent equilibrium (appears relatively constant for reasonable time). The viscosities were calculated at ten different shear rates in mPa for this plant oil and temperature. The shear stress and shear rate were calculated using formulas suggested for non-Newtonian fluid as shown in Eq. (7) [15].

$$\tau = \frac{M}{2\pi R_b^2 h} \tag{7}$$

where τ is shear stress; *M* is torque (Nm); R_b is radius of SP18 spindle (m) and *h* is the height of the spindle (m). The shear rate was calculated as shown in Eq. (8):

$$\gamma = 1.318 \times N \tag{8}$$

where *N* is the speed of spindle (rpm).

The experimental data were fitted to 4 models (Eq. (2) – Eq. (5)) by using common mathematical software.

3. Results and discussion

The rheology study and plant oil performance evaluation is discussed as follows.

3.1. Rheology study

This study is divided into three sections where the first section discusses on the effect of temperature on oil viscosity, the second section discusses the effect of shear rate on oil viscosity and the third section shows the correlation of viscosity, shear rate and temperature.

3.1.1. Temperature dependence of oil viscosity

Plant oil from the hydraulic test rig was sampled every 100 hour operation. Fig. 1 shows the variation of oil viscosity with temperature. From the figure, it is well understood that the oil becomes thinner when the operating temperature increases. This phenomena occurs to all liquid, irrespectively they belong to Newtonian or non-Newtonian fluid. However, as noticed, the viscosity increases with aging period when tested for 40, 60, 80 and 100°C. Noticeable difference is noticed when tested at low temperature. Less difference is noticed at 100°C. This is due to the capability of the equipment to measure very thin fluid, where larger spindle is recommended for measuring thin fluid.

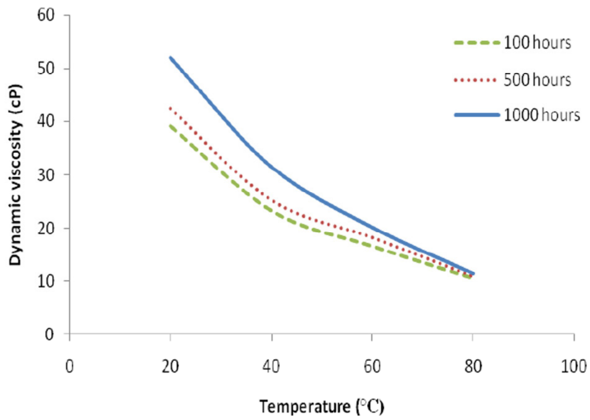

Fig. 1. Variation of plant oil viscosity with temperature.

The increase in viscosity with temperature can affect both mechanical and volumetric efficiencies. Higher viscosity means high internal fluid friction. In this respect, higher torque is required to run the system. This results in lower mechanical efficiency. On the other hand, thicker fluid results in less internal leakage through clearances in rotating components. This results in higher volumetric efficiency.

3.1.2 Shear rate dependence of oil viscosity

Fig. 2 shows the viscosity variation for oil samples taken from test rig at 0 – 1000 hours. The viscosity increases with operating hours. This is due to oil damage where polymerization occurs and contamination level in the oil increases. Pseudoplastic behaviour is observed for all samples. The increase in viscosity with reduce shear rate can result in rotating component to stall faster. The high dynamic viscosity at low shear rate means higher torque is required to start the rotating motion. This reduces the mechanical efficiency of the system.

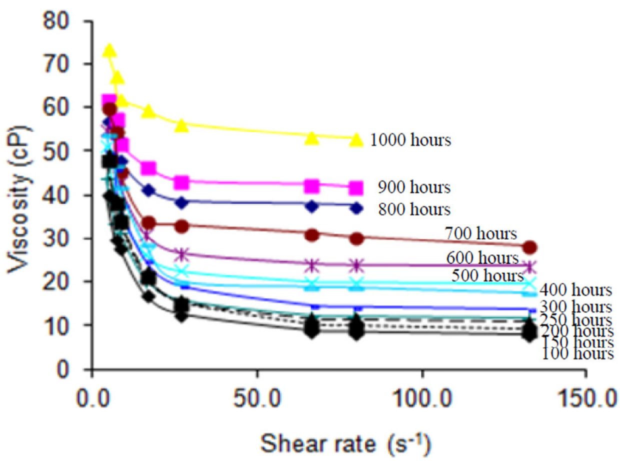

Fig. 2. Variation of plant oil with shear rate.

To further analyses the data, graph of viscosity versus shear rate is converted to log viscosity versus log shear rate form as shown in Fig. 3. From this graph, it can be seen that the curvature of viscosity versus shear rate can be made close to linear using this log-log format with regression of 0.9218

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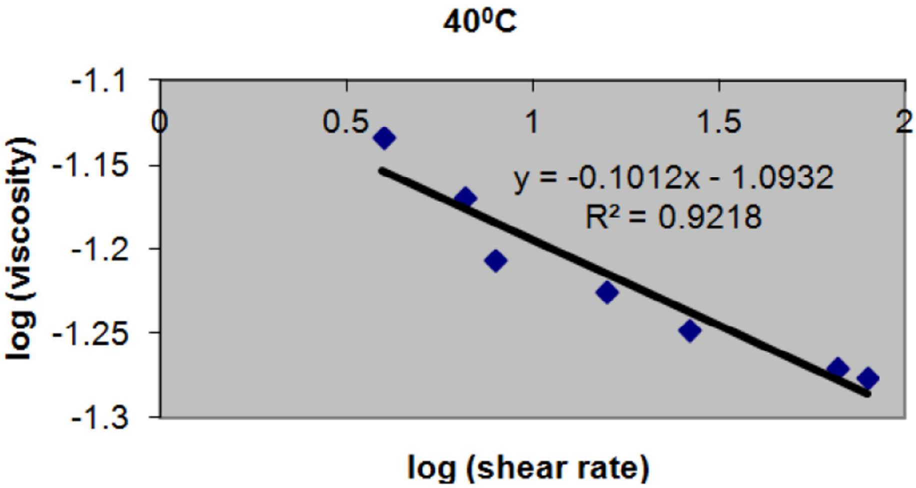

Fig. 3. Log viscosity against log shear rate plot.

Further study was made to investigate the resistance of the oil at low shear rate region. Several rheological models are matched to the experimental data as shown in Fig. 4. From the graph, it shows that the Cross and Careau models are the best models to represent the hydraulic oil (Eq. (2) – Eq. (5)). Surprisingly the Hershcel-Bulkley model does not fit well the experimental data between 20 to 40s^{-1} shear rates.

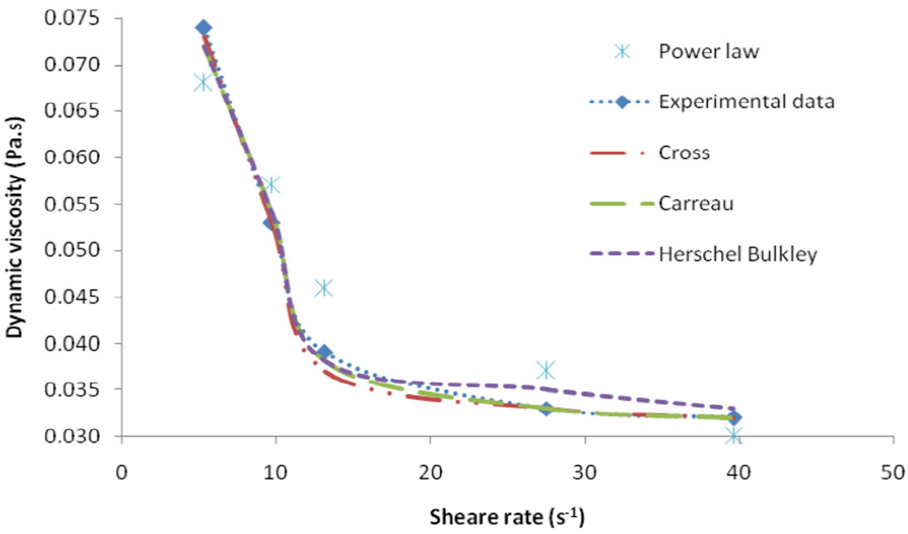

Fig.4. Fitted experimental data with various models.

3.1.3 Correlation of viscosity, shear rate and temperature

The viscometric properties of the plant oil are shown in Fig. 5. From a single diagram we can see how the viscosity varies with shear rates at different temperatures. It shows the viscosity decreases as shear rate increases from $3.9s^{-1}$ to $79s^{-1}$, and the viscosity is lowest when tested at 353.15 K. When temperature was lowered to 313.15 K, the viscosity increases respectively. This viscometric pictorial is very important since, in the hydraulic system, the oil is subjected to varying shear stress and heat and the variation can occur at the same time. If we can know the stress level and temperature level, then we can straight away find out the viscosity value of the flowing oil. Since both volumetric and mechanical efficiencies are dependent on oil viscosity, then theoretical relationship and actual performance can be evaluated.

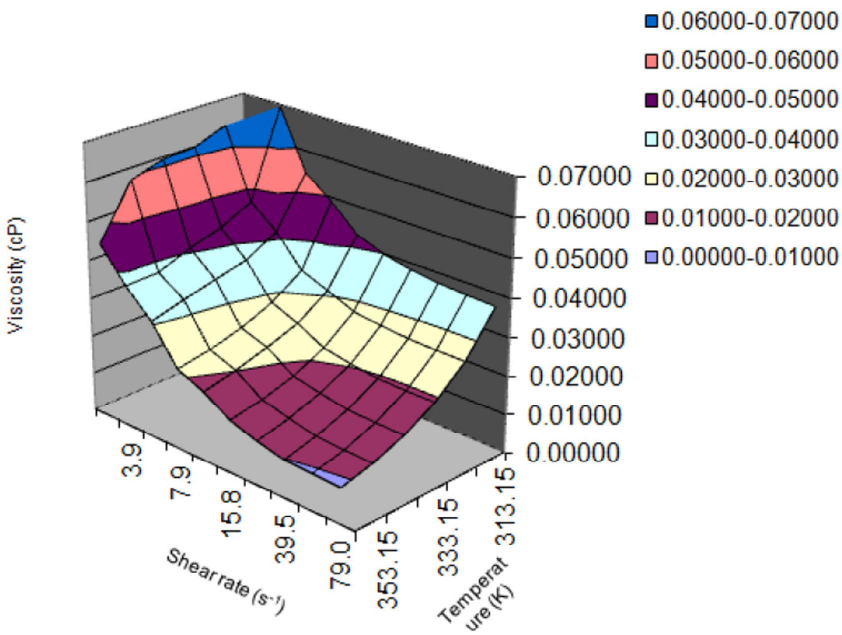

Fig. 5. Viscometric properties of plant oil.

4. Conclusion

From the rheological result of plant oil, it clearly shows that the temperature has a significant influence on the reduction of viscosity than the shear rate. The plant oil exhibits a non-Newtonian or specifically known as pseudoplastic behaviour which corresponds to a shear thinning relationship between viscosity (at low temperature) and shear rate. The shear rate dependence rheological models gave a good fitting on experimental data with R-squared value of 0.9218. The result seems to be promising and suggesting that the plant oil is suitable to be used as hydraulic fluid in future.

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